P-170: Subpixel Measurement of Superimposed Displays

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Abstract
We probe below the pixel barrier to address new means to measure overlapping projected displays. A low cost solution is developed to directly measure subframe pixel position to within .02 pixel, and a method to quantify thin line resolvability is introduced.

1. Introduction
By overlapping several projected displays the resolution of the resulting composite image can be higher than that of any single projector. This can be achieved by judiciously breaking the input into subframes using knowledge of the precise relationship between the overlapping displays [1]. In this study we used banks of 4 and 10 projectors as shown in Figure 1 where a MSE-based subframe generation scheme is used [2]. The complexity of the relationships between individual pixel overlaps is illustrated in Figure 2 where rectangular displays from different projectors result in differing non-rectangular areas. Such systems are calibrated with a single stationary camera that macroscopically captures whole-screen patterns from each projector to account for proper planar perspective transformation.

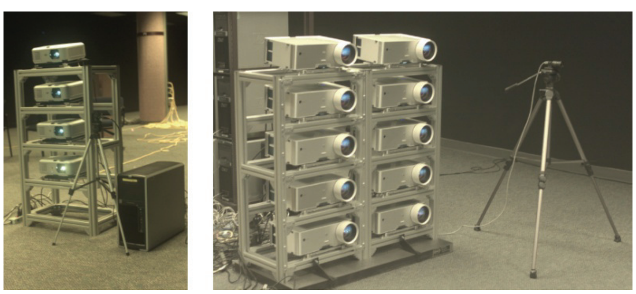

Figure 1. Four and ten superimposed projector systems used in this study.

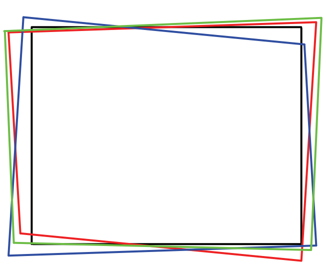

Figure 2. Four overlapped projections. Inter-frame pixel relationships are nonuniform

The objective of this paper is to develop tools to accurately measure such displays below the pixel barrier. The problem is unique to the extreme precision demands of overlapping displays. We attack this problem in two separate ways.

In the first approach we measure the actual position of subframe pixels within 2% of a pixel period throughout the image. As with other perspective correcting systems, a linear planar assumption is made in correcting subframes. We need a means for asserting that pixels are in their expected positions, and report placement errors throughout the image that could be due to a number of nonlinear effects. Such data can be used to correct the generation of subframes and increase the precision and quality of the composite display.

The second approach reported in this paper describes a means to quantify the resolvability of thin lines of subpixel dimensions in superimposed displays. Conventional measures of sinusoidal or grill-pattern modulation do not reflect differences that are seen for thin line rendering. Because the irregular overlap of projected frames makes rendering space-varying throughout the entire display, direct measurement is impractical.

2. Positional Ground Truth – Direct Measurement
The full-screen camera used to calibrate and correct the perspective geometry of the overlaid project frames cannot be used to measure pixel position accuracy better than the dimensions of a pixel. Our solution for precise positional information involved controlled projections captured by a still camera close to the screen.

To anchor our measurements, one of the projectors is identified as the reference projector, and is used as the absolute positional reference for all other overlays. The goal is to measure selected pixel locations from the other N projectors relative to the predicted closest reference projector pixel.

Figure 3 shows the screen with a setup image where the green targets indicate the regions where test patterns will be projected; in this example 20 regions are used. For a given target, a camera is setup at an angle at which none of the overlaying projected images are occluded by shadow. The lens-to-screen distance is chosen to be close enough so that the length of a projected pixel will be covered by at least 50 camera pixels (to meet our .02 subpixel precision criteria), but far away enough to minimize the camera angle skew.

To determine the reference projector coordinates, we start by projecting a checkerboard pattern of 11x11 pixels pattern surrounding the target pixel as depicted in Figure 4(a). The camera view of this is shown in (b). We want to know all the pixel locations and particularly the quadrilateral overlaid in red to determine a reference perspective transformation.

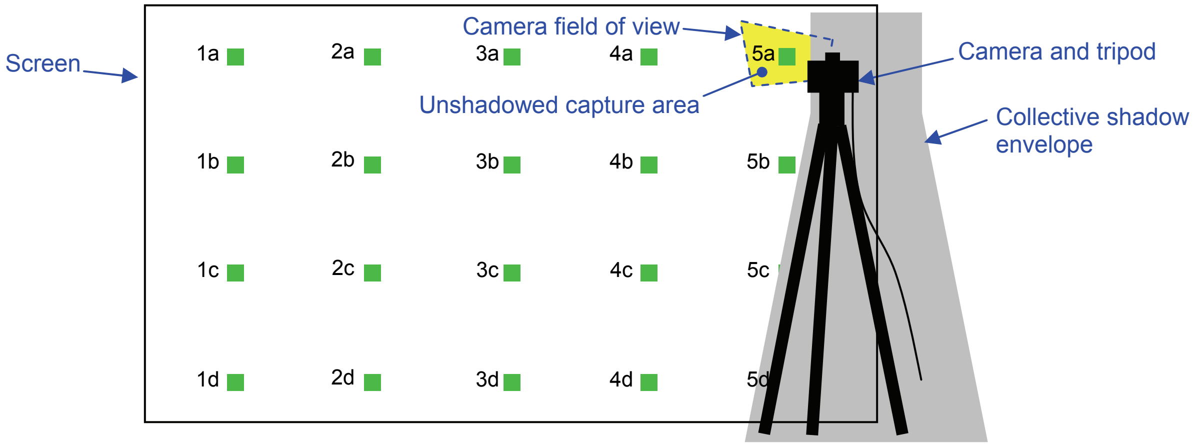

Figure 3. Projection screen with labeled projected targets, camera setup and occluding shadows.

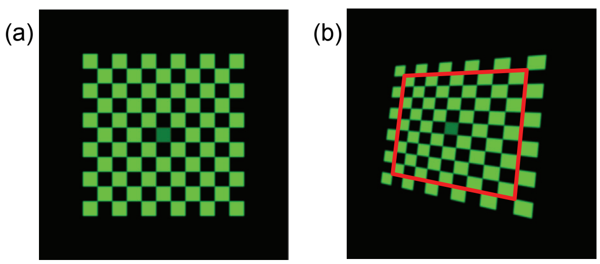

Figure 4. (a) Projected source reference pattern. (b) Camera captured version of the reference pattern.

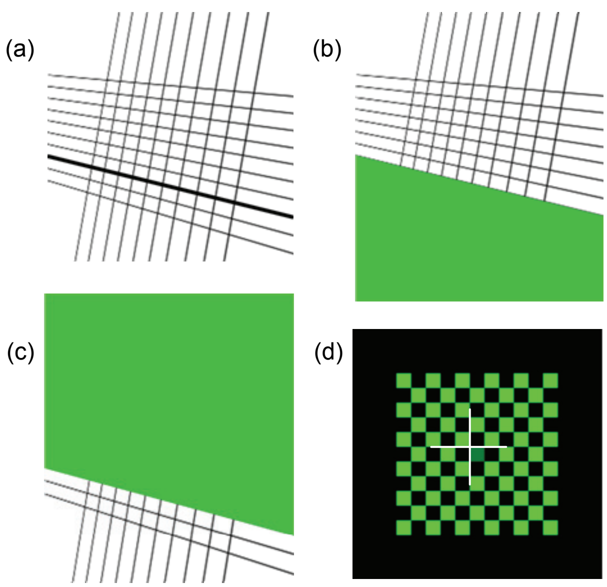

Figure 5. Establishing Reference Coordinates. (a) Pixel boundary lines to be determined. (b) First projected half-plane. (c) Second projected half-plane. (d) Perspective-corrected captured pattern.

The edges between the pixels in our captured image in Figure 4(b) are depicted in Figure 5(a). The location of the pixels in the reference pattern can be determined be locating these edges. The easiest way to automate this vision problem is to project a series of half-planes –green on one side and black on the other-- to define the pixel edges. By way of example, the bold line in Figure 5(a) is found by projected the half-planes as shown in (b) and (c) and captured. The edges are detected and averaged to cancel thresholding variation. This process is repeated for all 20 edge lines. The edge lines that comprise the quadrilateral in Figure 4(b) are then used to determine the homography transformation to achieve perspective correction. Armed with the reference perspective mapping, the image in Figure 4(b) is transformed to that in Figure 5(d) where the upper-left corner of the target pixel is identified by white cross hairs.

For a given non-reference projector, the closest predicted pixel to the target reference pixel is determined. A similar checkerboard pattern is projected around that pixel and is seen by the camera as shown in Figure 6(a). The pixel edges are found by again projecting 40 half-planes and extracting pixel boundary lines to locate pixel positions. To map this image onto the reference space, the perspective transformation found for the reference projector is used. In this space the pattern in Figure 6(a) will appear as shown in (b). Note that deviation from square reflects the angular offset between the reference and non-reference projectors.

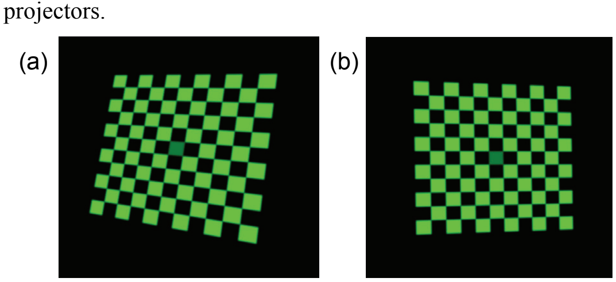

Figure 6. (a) Camera captured version from a non-reference projector, then (b) mapped onto the reference space.

Chromatic aberration is very significant at the magnifications used in this direct measurement process. To minimize this problem all pixels use only one of the three projector primaries. Green is used, as represented in our figures, because it is brighter than red or blue.

For each reference pixel and non-reference projected pixel, an error vector can be found between the predicted location of the nearest pixel, and the observed location. This is illustrated in

Figure 7. From the aggregate of error vectors for each target region of Figure 3, a full field error vector field is interpolated and extrapolated. This data is used for assessing the accuracy of the prediction model used, along with serving as a means for building the correction into the model.

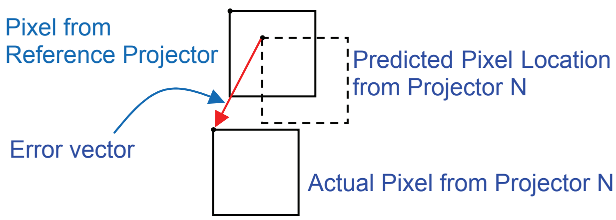

Figure 7. The relationship between a reference projected pixel and the predicted and actual locations of a non-reference pixel, and the resulting error vector.

We implemented the Direct Measurement system and automated the process. After aiming the camera at a target the system generates the 40 half-planes per projector, captures them in rapid succession, performs the correct perspective transformations, and records the precise pixel locations. Several measurements were made of our 4-projector display system, and results ascertained that when properly calibrated the subframe pixel accuracy is quite high, within a few percent across the entire image. This indicates that non-linear errors are not an issue. We have also found that thermal effect over time has a large effect on positional accuracy. Our measurement system achieves precisions of better that .02 projector pixel; this is due to the more than 70 camera pixels per projector pixel captured with the use of a connected SLR, in our case the 12 Mpixel Nikon D2X.

3. Thin Line Resolvability

Because of the irregular arrangement of overlapping pixels the performance of such displays varies across the entire screen. To quantify the ability of an overlaid projector system to resolve thin lines measurements are needed over the entire display to fairly average the performance. While sampling the screen with the direct measurement method described above is appropriate for acquiring positional accuracy which varies slowly, it would not be sufficient for thin line resolvability. The second part of this paper addresses this problem.

We built a highly accurate software simulator [3] to take the place of direct measurement, so that realistic output patterns could be generated measured and averaged across the entire screen in a reasonable amount of time. The simulator uses the same subframe generator and measured homographies used by each projector then upsamples the images by a factor of 10 in each dimension. The realism is achieved by rendering with a precise dot function; the dot function is generated by means of capturing and averaging several very high resolution instances of a single projected pixel. The simulator achieves strikingly accurate renditions of the actual overlaid projection systems.

In this study we specifically looked at thin line resolvability in dimensions at or below a single pixel width. As contrast measures do not make sense below the scale of a pixel we used a MSE-based metric.

Several hundred asymmetric thin-line grill (bar patterns) were run through our simulator averaging incremental input phases and then averaged over the entire screen. The spaces between black bars in these grills were chosen so that bar-to-bar interference was avoided; we found a space of 5 projector pixels to suffice for this purpose. Figure 8 illustrates the nature of the dimensions of an example pattern for testing lines of width ¼ in units of a projected pixel.

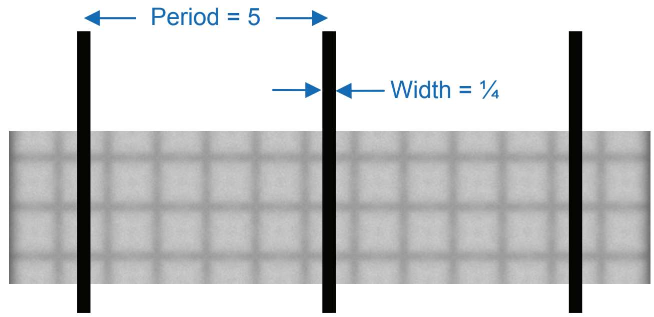

Figure 8. Dimensions of an input test pattern (shown on a background of DLP projected pixels for size reference).

The resulting measures support what is observed on the screen: subpixel lines are better resolved with multi-projection systems. Results of our thin line measures are plotted in Figure 9 for 4- and 10-projector systems, a single projector, and a single double-resolution projector, and a single "wobulated" projector. Wobulation [4] is an alternate form of overlaid projection where the microdisplay of a single projector is shifted at very high speed so that subframes are offset from each other in a regular way. Figure 10 illustrates the relative pixel locations of a 4-position wobulated system. Unlike the overlay of several projectors, pixels in wobulated subframes are uniformly spaced, however the resulting display does not enjoy the brightness increase.

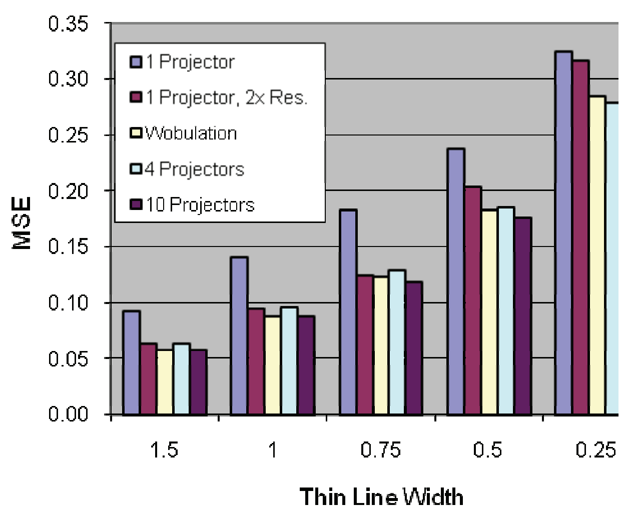

Figure 9. Results of thin-line resolvability tests.

The input grill thin line widths in Figure 9 are in terms of a projector pixel size, and MSE is normalized so that an all black image has MSE = 0.5. The surprise is that overlaid projector solutions have less error than true higher-resolution projectors. As we are using and modeling DLP micro-mirror projectors, the improved performance of overlaid projectors is attributed to the fact that the DLP "screen door" effect (due to inter-mirror gaps) is appreciable at these scales, and overlaid displays mitigate this problem.

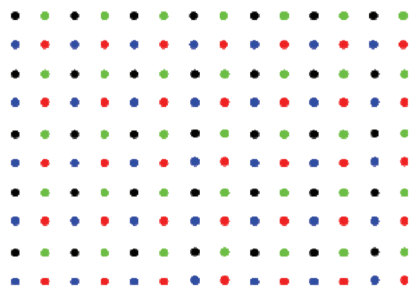

Figure 10. Interframe pixel positions for a single projector with wobulation. Each color represents a different shift.

4. Closing Remarks

Alternative means to directly measure displays with the level of accuracy we are achieving are much more costly. Most involve special sensors with high precision mechanical positioning to assure accuracy. Past examples include the custom-made and expensive motorized gantries used for measurement at the USC Entertainment Technology Center, Stanford University's Digital Michelangelo project, and National Gallery of London's high resolution painting capture system. Some methods [5] claim subpixel accuracy but just barely under one pixel, over an order of magnitude coarser than our method. Other approaches to subpixel calibration include the use of Gaussian blobs [6], and the use of reprojection error to measure accuracy using a quadratic model [7]. The proposed technique offers a lower cost solution and provides flexibility in capturing even for in situ applications. It is important to point out that the framework described here can be extended to support measurement for non-planar cases; instead of homographies to correct the camera space, the higher order surface would simply be fitted.

For thin line resolvability the traditional metric is contrast modulation [8], and more recently a version based on Fourier energy [9] which we have also used [3] for conventional frequency measures. However as overlaid displays break new ground below the pixel barrier we need new techniques as those reported in this study to measure performance.

5. References

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